PETROLOGY AND STRATIGRAPHY OF THE BRAYTON DISTRICT, NEW SOUTH WALES

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(Plate XVI)

Synopsis

An angular unconformity separating Upper Ordovician beds from (?) Silurian sediments and basic and acid volcanics has been mapped in the Brayton area. It is shown that the fine-grained silicic igneous rocks constitute a series of contemporaneous volcanic flows within the (?) Silurian succession, a conclusion at variance with earlier opinion. These volcanic rocks and the Marulan batholithic rocks are therefore distinct and separate entities. The hybrid zones of previous workers are re-interpreted as zones of increasing metamorphic grade where intrusion of granitic rocks into the silicic volcanics produced a contact aureole. A Tertiary dolerite body and two Tertiary basaltic flows exhibit closely correlative mineralogy, while the dolerite shows limited upward differentiation.

INTRODUCTION

The Brayton area lies approximately 130 miles south-west of Sydney, 10 miles north of Marulan. About 12 square miles were mapped in detail as shown in Fig. 1.

Upper Ordovician slates, quartzites and phyllites have undergone much regional deformation, culminating in an isoclinally folded sequence with a macroscopic meridional trend and approximately vertical dips. The (?) Silurian succession, which includes three distinct units, overlies the Ordovician rocks with angular unconformity. At the base, a series of shales, sandstones and calcareous siltstones with a general north-south strike and steep westward dip outcrop. Succeeding these sediments are basic volcanic flows with rare sedimentary lenses and a small limestone pod. Extensive silicic volcanic flows ranging from toscanites to dacites with some tuff bands comprise the youngest unit.

Field and petrological evidence indicates that the (?) Silurian sediments, basic volcanics and silicic volcanics constitute a conformable sequence and have shown synchronous response to low-grade metamorphism and regional deformation superimposed on the already deformed Ordovician sequence.

Granitic rocks forming part of the Marulan batholithic complex have intruded these Palaeozoic strata, producing contact metamorphic effects within an aureole at least one mile wide. An intermediate dyke of unknown age intrudes one of the granitic bodies.

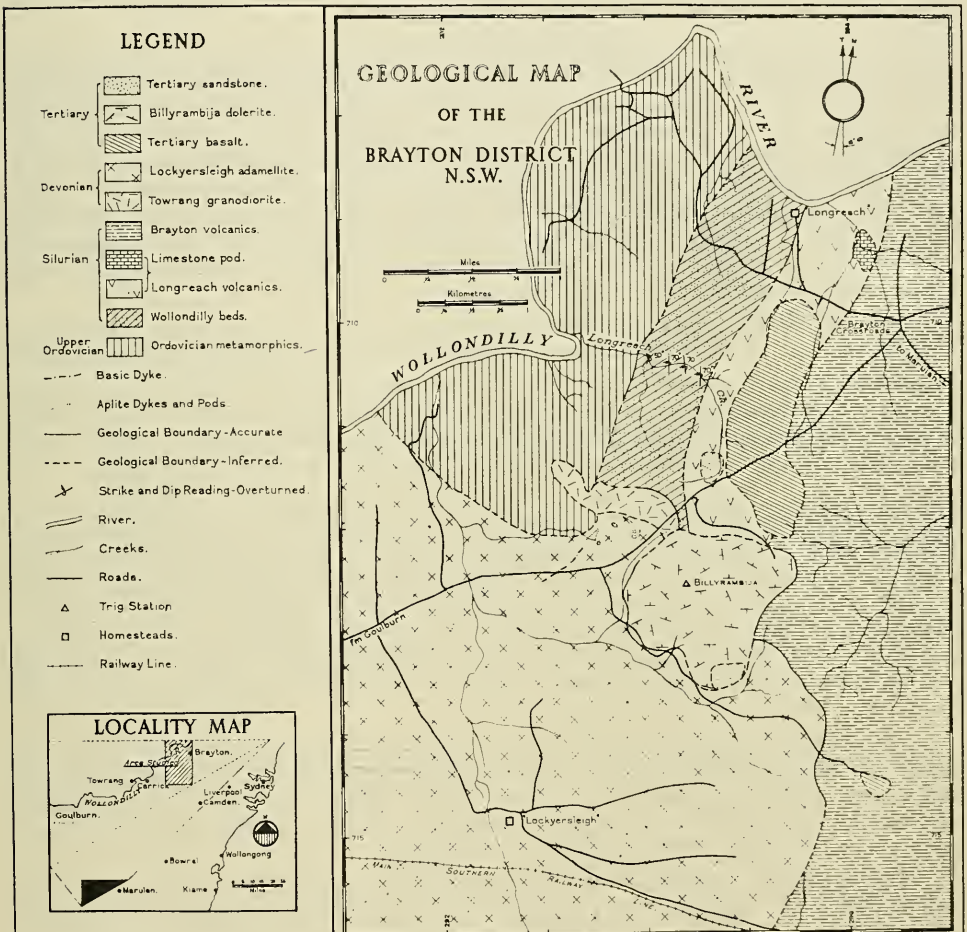
The remaining rocks are Tertiary in age. These include the Billyrambija dolerite, two basalt flows, and the associated Tertiary sediments, which are rich in a fossil flora.

PREVIOUS WORKERS

First geological observations made in the area were those of Clarke (1845). He stated that the Wollondilly River from its source to the junction with Paddy's River cut through igneous and metamorphic rocks which were laid bare over a considerable area between the Cookbundoon and the Uringalla.

Craft (1928) recorded that the Lower Palaeozoic rocks of the Wollondilly area are mostly Silurian and Devonian and " . . . consist of quartzites, slates and claystones together with some shales and intrusive granites. The general strike is about 10° east of north . . . ".

Woolnough (1909) investigated the general geology of the Marulan-Tallong district, to the south of Brayton. More detailed petrological studies on the Marulan batholithic rocks at South Marulan were carried out by Osborne (1948). Lovering (1950), Svenson (1950) and Osborne and Lovering (1952) studied in detail the " quartz porphyrites " and " quartz porphyrite hybrids " at South Marulan. These rocks are similar to the silicic volcanics at Brayton.



In a series of papers, Naylor (1935*a*, 1935*b*, 1938, 1939 and 1949) outlined the general geology of the Goulburn district. Of these, the first and last papers are particularly pertinent as rocks of the Brayton area are mentioned. Ordovician and Silurian boundaries, the extent of the Marulan Batholith and Tertiary basic igneous rocks were mapped on a scale of four miles to an inch. No differentiation into formations was effected, while the silicic volcanics were included as an integral part of the Marulan Batholith.

Browne (1933) first mentioned the dolerite outcropping at Billyrambija Trig., near Brayton. This he considered to represent a denuded Tertiary sill.

Ordovician Rocks

The Ordovician strata are typically highly deformed, have a regional meridional trend, are steeply dipping westward, and contain an Upper Ordovician graptolite fauna.

Primary bedding is defined by alternating layers of dark blue-grey carbonaceous slates and quartzites, both ranging typically from five to 12 feet in thickness. Within the quartzite layers are occasional fine bands of phyllitic siltstones six inches to 12 inches in width.

Structure: These beds probably lie on the overturned limb of a macroscopic fold or fold system which also involves the (?) Silurian sequence. Beds are almost vertical and all foliations measured are steeply dipping. Two fold types are evident on a mesoscopic scale. The first comprises similar folds with attenuated limbs and wider hinge areas. Wavelength is about 10 feet, with a comparable amplitude, the strike of the axial plane being approximately east-west. The axis is vertical; the fold surface is primary bedding. The second comprises small isoclinal folds with average wavelength approximately one foot and amplitude of two to four inches. The axial plane is vertical and strikes east-west, while axes plunge steeply westward.

Slates exhibit greater deformation than the more competent quartzites. The degree and style of deformation are not constant throughout the sequence.

Two further penetrative structural elements occur. One is a mineral streaking, approximately axial plane for the small isoclinal folds. The other is a layering defined by lenticular pods and isolated small closures. These show somewhat random orientation, but an overall east-west trend is evident.

Age and fauna: The dark grey carbonaceous slates yield two graptolite forms, *Climacograptus bicornis* and *Dicellograptus* sp. An age of Upper Gisbornian to Bolindian may thus be deduced (Thomas, 1960). Naylor (1949) previously recognized *Climacograptus bicornis*, *Diplograptus quadrimucronatus* and *Dicellograptus complanatus* in the vicinity of Brayton, but no precise locality was given.

Petrography: The quartzites consist of detrital quartz grains with rare felspar laths in a matrix of sericite and chlorite. Characteristic heavy minerals are smoky blue to blue-green pleochroic tourmaline, brownish-yellow to olive-brown pleochroic hornblende and opaque grains.

The matrix, forming up to 40% of the rock, has an incipient microscopic layering. Quartz shows evidence of deformation, including undulose extinction, Böhm lamellae and growth of small strain-free grains at sub-grain boundaries. Strings of tiny inclusions as well as apatite and zircon needles indicate a possible igneous origin for at least some of the quartz.

The phyllitic siltstones are compositionally equivalent to the quartzites. Macroscopically, the sheen and crenulations on penetrative surfaces are those of true phyllites.

The slates contain quartz (50%), sericite (20%), carbonaceous matter (18%) and opaque granules with rare zircon and tourmaline.

Contact metamorphism: The metamorphic grade attained by the pelitic rocks close to the granitic contact appears to be consistent with that of the hornblende hornfels facies. Quartz-muscovite-biotite-cordierite is the characteristic assemblage. The carbonaceous slates show development of andalusite needles up to 4 mm. long. Retrogression of the andalusite to sericite aggregates is ubiquitous.

(?) Silurian Sequence

As the age of this sequence cannot be strictly defined, it is referred to as (?) Silurian thus. The (?) Silurian beds are separated from the Ordovician rocks by a distinct angular unconformity which is discussed in detail below. Three units may be distinguished by lithological differences. These are the Wollondilly beds, Longreach volcanics and Brayton volcanics in ascending stratigraphic order. Their conformity is indicated by structural features including close correspondence of dips, strikes and orientation of the two ubiquitous joint sets. All (?) Silurian rocks show comparable mineralogical adjustments to a low-grade metamorphic environment. Thus synchronous deformation may be inferred.

Wollondilly Beds

A measured section extending from the unconformity against Ordovician rocks (29387150)* to the top of the Longreach volcanics (29497150) indicates the thickness of this unit is approximately 2,800 feet.

Four hundred feet of calcareous siltstones containing a brachiopod fauna succeed a thin conglomerate band (about five feet thick) which defines the base of the sequence. The remainder consists of interbedded sandstones and shales. Two prominent joint sets of consistent orientation dominate these rocks and bedding is often discernible only as a gross lithological layering. A penetrative cleavage is developed in the fine shale bands.

The Wollondilly beds and Ordovician rocks are unconformable. Because of overturning, the Ordovician overlies the (?) Silurian in the field. Angular unconformity is based on the following criteria :

(1) The two distinctive faunas indicate an hiatus at least from Upper Ordovician to possibly Upper Llandovery.
(2) The lithologies and structural complexity of the Ordovician rocks which must have suffered regional deformation before (?) Silurian sedimentation are distinctive.
(3) The trend of the boundary is in places transgressive to the strike of the (?) Silurian strata and suggests a gently undulating depositional surface.
(4) A conglomerate bed at the base of the (?) Silurian sequence contains pebbles from the Ordovician succession.

Sedimentary structures including current bedding, small-scale minor graded bedding, load casts and trace fossils indicate the sequence has been overturned. That bedding dips more steeply than the dominant cleavage, if this is axial plane cleavage, also supports overturning.

Age and fauna : The calcareous siltstones contain a profuse brachiopod fauna : fossils are abundant parallel to original bedding planes. Preservation is extremely poor but three forms were identified.

The first is characterized by ornamentation typical of *Atrypa*. Absence of further distinctive features precludes determination. The second is a delthyrid brachiopod, internal moulds of pedicle valves being preserved. Thus a maximum time span from Lower Silurian to Middle Devonian is indicated. This brachiopod could be *Howellella* sp., which would refine the time interval to from Upper Llandovery to Gedinnian. However, identification is not unequivocal due to the absence of definitive brachial valves. The remaining brachiopod occurs as internal moulds of brachial valves and has features consistent with those of *Schuchertella* sp., which is a Lower Devonian form (N. M. Savage, pers. comm.).

The unconformity between Ordovician and (?) Silurian beds is thus firmly established on faunal grounds. Because generic attribution cannot be positively made, the sediments containing the brachiopod fauna are tentatively called (?) Silurian.

* Grid references refer to the Goulburn 1 : 250,000 sheet SI 55–12.

Naylor (1949) considered these beds to be Lower Silurian, based on the lithological similarity with the Jerrara Beds near Bungonia, which yields a Lower Silurian graptolite fauna. He assigned an Upper Silurian age to the limestone pod in the Longreach volcanics because of the profusion of Upper Silurian limestones in the Goulburn district.

Petrography: The calcareous siltstones consist of approximately 30% carbonate, 30% quartz, 20% plagioclase and 20% interstitial chloride. Subangular quartz granules are generally less than 0·1 mm. across, and show serrated edges. Plagioclase laths up to 0·3 mm. long are An_{0-5} where unaltered to chlorite and zeolitic minerals. Carbonate occurs as granular aggregates possibly detrital in origin and as patches up to 0·5 mm. across, apparently replacing original matrix. Authigenic chlorite occurs as a cement. Where developed, massive or spherulitic aggregates of chlorite randomly replace plagioclase and original matrix. The chlorite is pale green, non-pleochroic and isotropic.

Detritus and matrix of the sandstones and shales are identical, only grain-size being distinct. Quartz, felspar, zircon and hornblende, tourmaline and opaque grains comprise the detritus. Grains are subangular and sorting is fair.

Quartz (60% to 70%) is of two types: angular grains with sharp extinction and subangular grains with undulose extinction and sometimes showing sub-grain development. These grains also contain strings of tiny particles and acicular zircon crystals. Marginal serration of all quartz is typical.

Felspar ranges from 5% to 20% in mode and is extensively altered to sericite and chlorite. Some show vestiges of multiple twinning but composition cannot be determined due to alteration. Interstitial material includes abundant sericite as fibrous aggregates which often encroach on detrital plagioclase margins. A colourless or pale green isotropic chlorite is subordinate. This cement constitutes up to 20% of the rock.

Contact metamorphism: The metamorphic rocks may be divided broadly into lower and higher grade assemblages dependent on distance from the granitic contact. Only original sandstones and shales outcrop within the aureole and observed assemblages are as follows:

(1) Lower grade:
Quartz-albite-muscovite-biotite
Quartz-muscovite-chlorite-opaque minerals

(2) Higher grade:
Quartz-muscovite-cordierite-biotite
K-felspar-biotite-plagioclase-corundum.

Different assemblages probably reflect the original composition of the sediment, although no silica-poor rocks were found outside the aureole. Lower grade rocks are consistent with parageneses of the albite-epidote hornfels facies, those of higher grade rocks generally lie in the hornblende hornfels facies. However, where potassium felspar is associated with corundum, pyroxene hornfels facies may be indicated.

Longreach Volcanics

The Longreach volcanics comprise a series of basaltic flows best exposed at 29567088. Outcrops extend over about half a mile between the Wollondilly beds and the Brayton volcanics. As flows are now vertical, this represents the thickness of the sequence. Small bands of sediment occur rarely between these flows and a small limestone pod outcrops at 29637092. Trend of flows is meridional, while two sets of prominent vertical joints are developed with orientations consistently 290° and 245°, as in the Wollondilly beds.

At 29557057 basaltic dykes transect the Wollondilly beds. These intrusions may represent feeder dykes for the flows of the Longreach volcanics as they show analogous low-grade alteration. Dykes show no preferred orientation and thus were not controlled by any pre-existing structural elements.

Petrography : The basalts are extensively altered and similar to spilitic basalts in fabric, mineralogy, chemistry and geological occurrence—the four criteria discussed by Vallance (1960). Three distinct types of alteration are evident, based on the dominant phases : (*a*) chlorite-epidote-tremolite, (*b*) chlorite, and (*c*) prehnite-calcite. Mutual gradations exist with no systematic distribution of alteration types.

The basalts generally show an intersertal texture with glomeroporphyritic aggregates of augite, plagioclase or augite and plagioclase. Flow foliation is evident but often obscured by alteration ; amygdales abound. A subvariolitic texture is common (e.g. 33692*). Quartz xenocrysts are abundant ; these generally show no mantling by pyroxene or evidence of reaction.

Plagioclase occurs as microlites, laths and glomeroporphyritic aggregates of laths up to 1 mm. long, with composition about An_5. Swallow-tail terminations indicate rapid chilling. Relict *augite* crystals have $2V_x=60°$, $Z \wedge c=40°$ and are colourless. Subhedral grains range from 0·5 mm. to 2·0 mm. across ; glomeroporphyritic aggregates are common. The original mesostasis has been almost completely obliterated. It was probably glassy to cryptocrystalline ; 33692 shows glass shards pseudomorphed by chlorite. Felspar microlites, tremolite needles, turbid sphene granules, chlorite and a felted layer silicate now constitute the groundmass.

A typical chlorite-tremolite-epidote assemblage is present in 33694. *Epidote* occurs as granular aggregates, prismatic crystals or sheaves of bladed crystals. Colourless granules replace plagioclase, but most epidote lines or fills amygdales. Optical properties are highly variable, often within the one crystal, some being pleochroic from bright to pale yellow with $2V_x=70°$, some being colourless with $2V_z=15°$. Two types of *chlorite* are present. One is colourless and isotropic, the other pleochroic from pale blue-green to pale yellow-green and shows brilliant anomalous blue interference colours. The chlorite generally replaces augite but may also infill or line amygdales. *Tremolite* occurs as felted aggregates of acicular needles (*ca.* 0·2 mm. long) in amygdales, as tiny needles (less than 0·1 mm. long) in the groundmass and as large rods associated with altered augite. It is generally colourless, but larger laths may be faintly pleochroic from colourless to pale blue-green. $2V_x$ is about 80°, $Z \wedge c$ is about 20°. Rare prehnite occurs as spherulites replacing augite and groundmass or infilling amygdales.

Dominant chloritic alteration is shown in 33687 and 33692. Relict augite and original glass shards (e.g. 33692–3) are altered to pale green chlorite showing brilliant purple anomalous interference colours. Amygdales are typically infilled with calcite or quartz, with or without chlorite. Felspar laths are extensively sericitized.

Prehnite-calcite alteration is typified by 33690–1. Here felspar shows no clouding. Augite is much altered to radiating sheaves of prehnite closely associated with patches of chlorite. *Prehnite* is optically positive with 2V ranging from 40° to 60° within a crystal. A pinkish hue in plane polarized light may be due to included haematite. Prehnite occurs as spherulites about 0·3 mm. in diameter, replacing augite and groundmass non-selectively. It also occurs as massive or sheaf prehnite where it pseudomorphs phenocrysts, appears not to replace the groundmass and is invariably rimmed by opaque grains. Abundant *calcite* is intimately associated with sheaves of prehnite and also occurs as ragged anhedra up to 3 mm. across and as amygdale infillings. Tremolite, sphene and epidote are present in the groundmass. Small orange spherulites are dotted

* Five-figure numbers used throughout the text refer to rocks in the Sydney University Geology Department collection.

sparsely throughout the prehnite. Amygdale assemblages include laumontite (?)-prehnite-calcite and quartz-calcite-chlorite-opaque minerals.

Contact metamorphics: In the lower grade rocks (e.g. 33701, 33709, 33711) the characteristic assemblage includes tremolite-actinolite, plagioclase, calcite, quartz, minor sphene and opaque grains. Plagioclase-actinolite-calcite assemblages appear to be analogous to patches of prehnite-epidote-chlorite in rocks outside the aureole. Plagioclase (*ca.* An_{44}) occurs as granoblastic aggregates of anhedral grains and as tiny laths in the groundmass. Tremolite-actinolite pseudomorphs original glomeroporphyritic pyroxene and occurs as a felt of tiny laths and needles replacing the original mesostasis. It is pleochroic with X=pale yellow-green, Y=colourless, Z=pale blue-green. $2V_x$ is 80°: $Z \wedge c$ ranges from 15° to 20°. Refractive index β is 1·620.

The higher grade rocks develop two distinctive types of assemblages, one abundant in pyroxene, the other dominated by hornblende and plagioclase. Both types still retain features of the original basaltic fabric. The texture is invariably blastoporphyritic; original amygdales and quartz xenocrysts are recognizable, although both are recrystallized and the former have mineralogically adjusted. The patchy, variolitic aspect of the flows is also preserved.

Hornblende-plagioclase rocks are the more abundant. The mineral assemblage comprises hornblende, plagioclase, quartz, sphene, epidote, opaques, potassium felspar and sphene. Hornblende pseudomorphs original augite glomeroporphs, occurs as discrete rods up to 2 mm. long and forms a groundmass network. Pleochroism with X=yellow, Y=bright yellow-green, Z=blue-green is distinctive. $2V_x$ is high, *ca.* 85°, $Z \wedge c$ is *ca.* 20° to 24°. Retrogression to a yellow uralitic product ranges from incipient to extensive. Plagioclase, An_{52} to An_{56} occurs as euhedral laths up to 0·5 mm. long. Pyroxene-rich assemblages occur as veins or patches in the normal hornblende-plagioclase rocks. Minerals present are diopside, rare hedenbergite, plagioclase (An_{58}), calcite, scapolite, hornblende, sphene, garnet, epidote and rare opaque granules.

Brayton Volcanics

The youngest unit within the (?) Silurian succession represents a period of silicic volcanic activity. Toscanites, dacites and tuffs, which extend beyond the area mapped, outcrop over about one mile normal to strike. As the sequence is now vertical, this represents a thickness of 5,000 feet. Evidence for vertical tilting is based on (*a*) marked variation in rocks types on a foot scale stratigraphically, while a few distinctive flow types may be traced for over a mile in a north-south direction and (*b*) the apparent conformity of all the (?) Silurian rocks.

Age and geological relationships: The silicic volcanics were extruded prior to emplacement of the Marulan batholithic rocks. Contact of the Brayton volcanics with the granitic rocks is sharply delineated and intrusion by the Lockyersleigh adamellite is undoubted, as evidenced by the metamorphic effects discussed below. Four factors are most significant:

(1) These rocks are extrusive as is first indicated by their conformity with the Wollondilly beds and the Longreach volcanics. The Brayton volcanics form an integral part of the stratigraphy.

(2) Recognition of flow units, presence of tuff bands, flow lineation (Plate xvi, fig. 1) and relict glass shards (Plate xvi, fig. 2) indicate a volcanic origin. Evidence for extrusion is observed in several exposures whose brecciated nature indicates explosive activity. Angular toscanite fragments (1 in. to 6 in. across) are separated by a network of essentially epidote-hornblende domains up to 1 in. in width. This network probably represents original glass which formed a groundmass for the breccia.

Subsequent low grade alteration effected chemical redistribution involving both glass and breccia fragments.

(3) The intrusive nature of the granitic rocks demonstrates the older age of the Brayton volcanics. That considerable time intervenes is a logical result of the conformity of the whole (?) Silurian sequence. A period of structural deformation and low grade rock alteration must have occurred before introduction of the granitic rocks. As discussed above, the Brayton volcanics are tentatively assigned to the Upper Silurian although a Lower Devonian age is not precluded. The age of the Marulan Batholith on present data may be pre-Upper Devonian to Carboniferous (see below).

(4) Chemical evidence is inconclusive as the two chemical analyses available (Osborne and Lovering, 1952) demand no genetic relationship between the silicic volcanics and granitic rocks.

In summary, the extrusive nature and approximate time of extrusion indicate that the Brayton volcanics and the Marulan batholithic rocks are discrete entities.

This departs from the concepts of previous workers, notably Woolnough (1909), Naylor (1935*a*) and Osborne and Lovering (1952), who considered the silicic volcanics to be shallow intrusions intimately associated in time and possibly comagmatic with rocks of the Marulan Batholith.

Petrography: Mesoscopically the silicic volcanics are fine to medium grained and range from dark grey green to greenish blue; flow foliation is sometimes visible. Phenocrysts of euhedral quartz, zoned plagioclase, alkali felspar, hornblende and biotite averaging 1 mm. to 4 mm. in length are set in an aphanitic groundmass.

Microscopically, many of these silicic volcanics are tuffaceous with fragmented phenocrysts in a once glassy mesostasis. Primary phenocrysts are quartz, plagioclase, alkali felspar, biotite, hornblende and rare pyroxene. Accessories include opaque oxides, sulphides, zircon and apatite.

Quartz phenocrysts up to 4 mm. across constitute 10% to 30% of the rock and typically show embayments. Euhedral outlines suggest an original phase. Strings of tiny particles and inclusions of felspar, zircon and apatite are common. Fracturing of phenocrysts and undulatory extinction are characteristic.

Plagioclase (10% to 30% of the rock) occurs as subhedral laths and angular fragments, both compositionally identical. Extensive alteration to carbonate, sericite, epidote, prehnite and zeolites often obscures original compositions. Where determinations are possible cores are andesine and rims albite. Small laths are albitic (An_{3-6}) while larger grains show patchy albitization. *Potassic felspar* phenocrysts are not abundant but locally may reach 20% in some flows. Usually the potassic felspar is surrounded by a rim about 0·2 mm. wide of albite as indicated by staining. Alteration to sericite and carbonate is widespread.

Biotite (0–10%) occurs as phenocrysts and replacing hornblende. Laths may reach 2 mm. long. Most show kinked cleavages and shredding parallel to the basal cleavage. *Hornblende* phenocrysts are rare and often represented by small relict patches in areas of alteration. Pleochroism from olive green to mid brown is sometimes evident. Rare *hypersthene* may have been present more abundantly before alteration. The *groundmass* is typically cryptocrystalline and exhibits excellent flow structures. Staining shows, where grain size is resolvable, a granophyric (or granoblastic, if devitrified) intergrowth of quartz, potassic felspar and albite. Devitrified glass shards, following flow lineations, may constitute 50% of the mesostasis. Arcuate lenses of minutely crystalline quartz and more rarely alkali felspar appear to result from devitrification (e.g. 33729). Here, lenticular areas consist of parallel rows of tiny zeolite needles. Replacement of shards by chlorite has also taken place.

The classification of these silicic volcanics as toscanites and dacites with tuffaceous equivalents is based on observed modes now evident in the rocks.

Contact metamorphism—Petrography: The Brayton volcanics exhibit the effects of contact metamorphism in four main ways:

(1) Grain growth of the mesostasis obliterates all evidence of primary structures. A granoblastic intergrowth of quartz and alkali felspar with minor biotite replaces the original groundmass.

(2) Original mafic phenocrysts show progressive changes. Low grade alteration of pre-existing hornblende, pyroxene and biotite produced prehnite, sphene, chlorite, opaque grains and epidote prior to contact metamorphism. Approach to the granitic contact shows development of green "biotite" (interlayered chlorite and mica ?), then hornblende, or brown biotite.

(3) Contact metamorphism of minerals in veins previously formed by low grade alteration, produced assemblages such as epidote-diopside-garnet-amphibole-quartz-albite.

(4) Annealing recrystallization of large strained embayed quartz grains is evident (see Plate XIV, fig. 3).

Three broad zones which represent an increase in metamorphic response are observable progressing towards the adamellite contact. Their recognition is based on the degree of recrystallization of the groundmass and mineralogical changes.

33635 is typical of silicic volcanics on the outer edge of the aureole. The groundmass shows moderate recrystallization with no remaining flow structures. No zeolite phases persist and tiny flakes of pale green amphibole are scattered throughout. Quartz phenocrysts are unaffected, alkali felspars are extensively altered to sericitic patches, while plagioclase is mostly albitic and clouded with epidote, carbonate, chlorite and sericite. Original mafic phenocrysts are completely pseudomorphed by epidote associated with cloudy aggregates of sphene and leucoxene, or interlocking felts or pale green mica with flakes of blue green amphibole and minor epidote.

33648 shows a successive metamorphic response. The groundmass grain size has increased but quartz is still unaffected. Potassic felspar is completely altered to sericite and tiny quartz blebs. Original phenocrysts are all rimmed by a narrow zone, 0·1 mm. wide, of clear albite granules. Green-brown biotite and subordinate green chlorite occur. Outlines of original euhedral phenocrysts are no longer sharply defined.

The highest metamorphic grade attained is shown in 33740 and 33755, which exhibit hornblende-rich and biotite-rich assemblages respectively. The groundmass is granoblastic and the assemblages indicate probable attainment of upper hornblende hornfels facies conditions. Potassic felspar grains are not extensively altered and both felspars show incipient recrystallization. Quartz grains (see Plate XVI, fig. 3) show annealing crystallization where grains were originally strained. 33740 contains clots and strings of hornblende laths up to 0·1 mm. long. These are pleochroic with X=deep blue green, Y=dark olive green and Z=pale yellow green. $2V_x$ is *ca.* 70°, $Z \wedge c$ is *ca.* 20°. Associated sphene granules abound. 33755 exhibits decussate aggregates of biotite (Plate XVI, fig. 4) with each lath up to 0·5 mm. long. Rare amphibole laths and opaque grains may be associated with biotite, while sphene is absent. Opaque grains, zircon and apatite are constant accessories.

Thin sections 33645 to 33652 are representative of the explosive breccia discussed above. This outcrops at 29587139, close to the adamellite contact. Silicic volcanic fragments show zonation with an inner core of normal dacite or toscanite surrounded by a quartzofelspathic outer rim up to 15 mm. wide comprising a zone leached of mafic constituents. These are set in a " groundmass " of granular intergrowths of diopside, hedenbergite and epidote which may be penetrated by laths of amphibole. Irregular, clear quartz blebs, carbonate patches and garnet grains are evident. Rare porphyroblasts of albite occur, while tiny opaque and sphene granules may be locally abundant. These contrasted compositions arise from an original chemically homogeneous rock as indicated by the migration of mafic components from fragment peripheries. While the inner core of fragments is compositionally equivalent to the normal silicic volcanics, their leached rims are higher in alkali and silica content, and the inter-fragment area is enriched in iron, calcium and magnesium.

It has been suggested above that this breccia formed by explosive volcanic activity. Devitrification at low temperatures and pressures prior to granitic intrusions initiated chemical reorganization mainly involving the " groundmass " but also affecting fragment rims. The granite subsequently produced the observed assemblages (*cf.* Vallance, 1967).

Metamorphism and previous concepts: The relationship of the granitic rocks to the silicic volcanics closely parallels that of the granodiorite and " porphyrites " south of Marulan. They were studied in detail by Osborne and Lovering (1952) and Svenson (1950), following Woolnough's (1909) general observations.

Osborne and Lovering (1952) considered the " porphyrites " were intruded as a high-level sill into Lower Palaeozoic country rocks. With the " porphyrites " still at elevated temperatures, intrusion of the granodiorite took place. Through slow cooling hybridization by interaction of magma and porphyrite ensued. Three " hybrid zones " were developed exhibiting mutual gradations representing successive degrees of hybridization. This process involved migration of soda from the magma to be deposited as albite rims in the hybrids. Extensive hydrothermal activity supplied " vigorous solutions " which effected formation of epidote, sericite and chlorite in hybrid " porphyrites ". Diffusion into hybrids of TiO_2 and alkalis as well as concentration of CaO and MgO to produce hornblende and biotite was also invoked. Analyses of one porphyrite, two hybrids and the granodiorite were recorded.

No evidence of such chemical interaction was detected between rocks of the Brayton volcanics and the Lockyersleigh adamellite. A similar relationship was noted by Gould (1966) and Wass and Gould (1968) between the Tangerang volcanics and Glenrock granodiorite at South Marulan.

The silicic volcanics show both extensive alteration and response to contact metamorphism. Observed characters may be attributed to a metamorphic progression towards the granite contact in rocks already altered rather than to development of " hybrid zones ". These zones are probably correlative with the three stages of metamorphism discussed above. Compositional variations may be due to redistribution of components during previous low grade alteration and intrinsic chemical differences in individual flows.

The sodic rims on alkali felspars do not necessitate addition of sodium. This phenomenon occurs even in rocks removed from the influence of the granitic rocks and may represent complete subsolvus unmixing of sodic and potassic phases. Formation of hornblende and biotite clots near the granitic contact does not require concentration of CaO and MgO as the chlorite and epidote of outer zones could contribute required components.

Thus the present study of the Brayton volcanics indicates that a metamorphic progression rather than development of hybrid zones accounts for textures and mineral assemblages observed.

Igneous Intrusions

Two components of the Marulan batholithic complex are represented. These are the Lockyersleigh adamellite and Towrang granodiorite. A contact metamorphic aureole up to one mile in width is developed. Metamorphic assemblages produced in the intruded rocks have been discussed within each rock unit.

Lockyersleigh Adamellite

The Lockyersleigh adamellite was mapped over approximately three square miles (Fig. 1), but extends considerably southwards. Where exposed, contacts with country rock are sharp. Silicic volcanics of the Brayton volcanics were intruded by this adamellite and are cut by leucocratic veins derived from the intrusion. In places, exposures must be close to the roof of the intrusion as fine-grained phases are evident. Aplitic dykes, representing late-stage crystallization of the adamellite, contain miarolitic cavities lined with alkali felspar, smoky quartz and tourmaline crystals. Veins of epidote up to 2 mm. wide occur throughout the adamellite.

Petrography: The adamellite is holocrystalline, hypidiomorphic granular and shows a porphyritic texture with phenocrysts of alkali felspar, plagioclase, quartz and, rarely, biotite or hornblende. These minerals are duplicated in the groundmass. Abundant sphene, opaque grains, epidote, zircon, apatite and alteration products including chlorite, carbonate, and sheaves of muscovite and prehnite are present. *Quartz* generally constitutes 30% to 40% of the rock. Phenocrysts are up to 4 mm. across, anhedral and often embayed. Undulose extinction, Böhm striae and development of strain-free grains are common. *Potassium felspar* constitutes about 30% of the rock. Subhedral phenocrysts range from 4 mm. to 10 mm. long. The optic axial plane is perpendicular to (010); $2V_x$ is approximately 50°; extinction on (001) is parallel to (010) cleavage, and on (010) ranges from 7° to 9°. Thus the felspar is monoclinic or has very low triclinicity. The latter is doubtful as "tartan" twinning is absent (Laves, 1950). The composition lies in the range $Or_{85-70}Ab+An_{15-30}$ (Tuttle, 1952), and thus the felspar is an orthoclase low-albite perthite. Film and vein perthites are well developed: myrmekitic intergrowths are common. *Plagioclase* forms about 30% of the rock. Phenocrysts (2 mm. to 4 mm. long) show consistent core/rim compositional ranges of about An_{55} to about An_{22} respectively. *Hornblende* (absent in the Towrang granodiorite) occurs sporadically as euhedra or ragged subhedra; a reaction relationship giving biotite is often observed. It is pleochroic X=pale yellow, Y=grass green, Z=olive green. $2V_x$ is approximately 70°. *Biotite* comprises up to 5% of the rock. Pleochroism is X=orange brown, Y=pale straw yellow, Z=deep speckled chocolate brown. $2V_x$ is approximately 10°. Alteration to chlorite, muscovite, prehnite, carbonate and granular epidote is common. Modal *sphene* may reach 5%. It occurs as granular aggregates, but commonly as euhedra 0·5 mm. to 2 mm. long. Sphene is more abundant where hornblende is locally in excess of biotite. The intergranular groundmass forms 20% to 40% of the rock and comprises all mineral phases present in the rock.

Towrang Granodiorite

This granodiorite forms a small stock exposed at 294712. In outcrop it is approximately elliptical with east-west elongation. About one mile west of the area and one mile north of Towrang, a similar granodiorite is evident. These two masses may represent a single intrusion.

The relationship with the Lockyersleigh adamellite is obscure because of poor outcrop on the boundary. The grey and white rock is quite uniform in hand specimen although occasional pegmatite patches are noted. These occur as veneer-like pods up to one foot in diameter, but never exceeding one inch in thickness. Distinct from the Lockyersleigh adamellite, no tourmaline occurs in the granodiorite but pyrite is common in the pegmatite phases.

Petrography : In thin section the rock is holocrystalline, allotriomorphic granular. Minerals present are quartz, plagioclase, potassium felspar, biotite, opaque grains and accessory epidote, sphene, apatite, zircon, carbonate and muscovite. *Quartz* constitutes 30% to 40% of the mode and is typically anhedral and interstitial, although grains may obtain a maximum diameter of 3 mm. Well-developed Böhm lamellae and mosaic textures are evident. *Plagioclase* occurs as poorly terminated subhedra from 1 mm. to 4 mm. long and constitutes up to 40% of the mode. Compositions range from an average of An_{50} for the most calcic cores to An_{20} for outermost rims. Broad antiperthitic veins show rare development. Some large plagioclase grains have highly resorbed cores which appear to be accumulophyric. Vance (1962) attributes such textures to " patchy zoning ", arising from an intense phase of uneven resorption and subsequent re-precipitation and infilling by more sodic plagioclase. In rare grains with resorbed cores mosaic domains in optical continuity produce a patchiness on a 0·1 mm. scale and appear to control or be controlled by twin lamellae.

Potassium felspar constitutes 20% to 30% of the rock and occurs as anhedra up to 4 mm. across. The optic axial plane is perpendicular to (010) and straight extinction of (001) indicates a monoclinic structure. Extinction on (010) of 10° to 12° indicates a composition $Or_{65}Ab+An_{35}$ to $Or_{50}Ab+An_{50}$. Perthitic textures are variably developed : albitic rims and large segregations are rare while no myrmekite was detected.

Biotite tends to occur in aggregates and represents no more than 5% of the mode. Laths (0·2 to 1·0 mm. long) are pleochroic with X=straw yellow, Y=red-brown, Z=chocolate brown. Inclusions of zircon and apatite euhedra are common.

Emplacement and Age

Employing the genetic classification of Tuttle and Bowen (1958), the Lockyersleigh adamellite and the Towrang granodiorite both represent subsolvus or group II granites. All features observed are characteristic of plutons emplaced in epizonal regions (Buddington, 1959).

The age of these intrusions can only be determined broadly as post-Brayton volcanics (Upper Silurian to Lower Devonian) and pre-Tertiary. Regarding the Marulan batholithic complex as a whole, Naylor (1939) records Upper Devonian sediments with a typical Lambian fauna, resting unconformably on granitic rocks near Taralga and Bungonia. At South Marulan quarry, Upper Silurian limestone is metamorphosed by granite. Thus an age of Lower to Middle Devonian may be inferred on stratigraphic evidence. However, Evernden and Richards (1962), using the K/Ar ratio of constituent biotite of a granodiorite from Bungonia, determined an age of 307×10^6 years (Carboniferous). This apparent anomaly may be due to non-contemporaneity of all phases comprising the Marulan batholithic complex or to loss of original argon.

Tertiary Rocks

Two basaltic flows (see Fig. 1), the Billyrambija dolerite mass and scattered sediments represent Tertiary rocks present. Age of the igneous rocks is inferred from their intimate association with sediments containing Tertiary flora and from their petrological affinity to basaltic rocks in the Moss Vale region which have a Tertiary age as shown by potassium-argon dating (P. Wellman, pers. comm.).

Tertiary Sediments

Isolated small outcrops of Tertiary sediment are associated with the Billyrambija dolerite where they occur mainly at the base and the 100 feet contour level, and with the two flows. Lamination of relatively fine and coarse fractions on a centimetre scale is marked, each layer often exhibiting graded bedding. Detritus comprises dominant volcanic, plutonic and reworked quartz grains, together with altered felspar grains and aggregates, while hornblende, epidote and muscovite are accessories. This detritus appears to be derived directly from nearby sources such as the Brayton volcanics, the silicic intrusions and the Ordovician or (?) Silurian sediments. Extreme angularity of grains suggests little transportation. The interstitial material may be partly matrix and partly cement and constitutes from 20% to 30% of the rock. It consists of very fine-grained, heavily iron-stained siliceous material.

The flora is poorly preserved, but most specimens are dicotyledonous leaves belonging to the *Cinnamomum* flora. One well-preserved fragment is similar to *Cinnamomum polymorphoides*, McCoy, 1874. That the leaves may be placed in the family *Lauraceae* and compared with species of *Cinnamomum* is indicated by comparison with similar but well-preserved fossil leaves from Wingello, which are considered to belong to the *Cinnamomum* flora (D. Selkirk, pers. comm.). This flora is Tertiary or, less probably, late Cretaceous in age. However, such leaves are termed Tertiary as geologists, on topographic and physiographic evidence, have considered closely associated basalts to be Tertiary. The gradual accumulation of potassium-argon dating of such basalts (e.g. McDougall and Wilkinson, 1967) supports this in general and thus, with available data, it seems reasonable to consider these sediments Tertiary.

Billyrambija Dolerite

The Billyrambija dolerite has a maximum exposed height of 340 ± 10 feet and outcrops in an approximately circular pattern with a diameter of one mile. Field relations do not provide conclusive evidence on the mode of emplacement. However, it is suggested that it may represent a very high level intrusion, possibly disrupting unconsolidated sediment and reaching the surface in places. This is supported by the presence of chilled phases which form randomly placed knolls and shoulders, and the presence of blocks of Tertiary sediment at the 100 feet contour line which show random bedding orientations.

Three components of the dolerite are recognized : chilled phases, dykes and the main dolerite body. The *chilled phases* occur associated with Tertiary sediment and are mineralogically comparable to the dolerite. Phenocrysts of titanaugite rarely exceed 2 mm. in diameter ; olivines are typically skeletal and clouded with inclusions, are unzoned and have a composition about Fo_{85} ($\beta = 1 \cdot 680 \pm 0 \cdot 003$). Plagioclase ($An_{60}$ core to An_{45} margin) is abundant and laths often show swallow-tail terminations. The groundmass is extremely fine-grained but tiny pyroxene and opaque granules are evident. *Dyke rocks* are distinctive in mineralogy and field occurrence. Dykes apparently intruding the dolerite can usually be traced over a vertical height of 20 feet and vary from five feet to one foot in width. Wider dykes exhibit chilled margins. Euhedral titanaugite, olivine and plagioclase (core An_{50}, margin An_{40}) are set in a fine-grained groundmass dominantly composed of aegirine-augite and magnetite. Pyroxene phenocrysts may be mantled by aegirine-augite and are often densely clouded with magnetite granules. Olivine phenocrysts are zoned from Fo_{80} to Fo_{60} (core and margin respectively). Amygdales abound in dyke rocks and are filled with thomsonite, chabazite, natrolite, analcite, prehnite or clay minerals.

The Billyrambija dolerite comprises pyroxene (35–40%), olivine (13–28%), plagioclase (14–25%) and opaque grains (3%) set in a mesostasis (14–25%) of zeolites, tiny opaque granules, laths of K-felspar, flakes of aegirine and (?) kaersutite, analcite and secondary chlorite. Apatite needles up to 0·5 mm. long abound.

Titanaugite euhedra occur in two generations. Those of the first generation reach 5 mm. across, may occur singly or in glomeroporphyritic aggregates, and are commonly sub-ophitically indented by plagioclase. Inclusions of a cubic iron-titanium oxide, olivine and a colourless (?) pyroxene are common. Pleochroism with X = pinkish yellow, Y = pink, Z = mauve-pink is variable in intensity. Well-developed hour-glass structures are present. Zoning is striking and generally limited to the outer few millimetres of the large euhedra. Second generation pyroxenes are prismatic and reach a length of 0·5 mm., lack significant zoning, and are optically identical to the outer margins of large pyroxenes.

Olivine also occurs in two distinct generations, as subhedral to anhedral grains up to 0·5 mm. across and as euhedra up to 2 mm. long. The latter have compositions from about Fo_{70} to Fo_{85} as determined by refractive index and X-ray methods.

Plagioclase occurs as euhedral, zoned laths 0·5–2·0 mm. long. Cores exhibit compositional variation with upward progression from An_{85} to An_{63}, rims being up to 15 mol. per cent. richer in Ab.

Opaque minerals identified were ilmenite and titanomagnetite. *Ilmenite* occurs as laths which may be sub-dendritic in habit and represent 10% of opaque minerals present. *Titanomagnetite* occurs as octahedra up to 0·2 mm. wide. Compositions were estimated by measuring cell edges and using the curve of Basta (1957). Titanomagnetite from the lowest level was approximately 96% Fe_2TiO_4, that from the highest level 70% Fe_2TiO_4.

Modal analyses indicate that mild differentiation may have taken place within the dolerite body: there is an upward decrease in mode of olivine and plagioclase and increase in volume percentage of mesostasis. This is supported by the limited and preliminary compositional data on the plagioclases and titanomagnetites.

Tertiary Basaltic Flows

Two tertiary basaltic flows are evident (Fig. 1). The southerly flow is petrographically identical with the chilled phase of the Billyrambija dolerite. Perhaps the original extent of this latter body was greater than now observed, this flow representing a southerly projection of the Billyrambija dolerite.

The northerly flow is petrographically distinct, although still a typical alkali basalt. Extensive alteration, mainly due to weathering, has taken place. Pyroxene is rare; olivine euhedra up to 1·0 mm. long comprise 10% of the rock and are extensively altered. Plagioclase laths (30% of the rock) are zoned from An_{58} (core) to An_{45} (margin) and define a flow lineation. The groundmass may have been glassy; felspar microlites abound as well as fine opaque particles.

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